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Water and solar radiation productivity of double-crops in a humid temperate area

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Abstract

The intensification of agricultural systems including sequential double-crops provides a reliable platform to increase the water and solar radiation use in many humid temperate areas of South America, which are predominantly dominated by soybean as a sole crop. Our aim was to evaluate water and solar radiation productivity, as a measure of the whole system efficiency, in sole-crops and double-crops in a humid temperate area of Argentina (31.5º S, 60.3º W, 110 m.a.s.l). An experiment including spring wheat, flax, rapeseed, peas and soybean as sole-crops and the sequential combination of winter crops with soybean as a second crop was carried out during the 2007/08 cropping season. We measured soil water content and solar radiation interception in order to estimate crop evapotranspiration and total intercepted solar radiation as a measure of the total captured resource by crops. Water and radiation use efficiencies were calculated as a ratio between grain yield and the captured resource. Water and solar radiation productivity were calculated as the product of the proportion of annual offer (rainfall or incident solar radiation) of the resources captured by crops, i.e. the capture efficiency and the resource use efficiency to produce grain yield. Capture efficiency was higher in double-crops than in sole-crops (average 0.99 vs. 0.51 for water and 0.41 vs. 0.18 for solar radiation). In contrast, the averages of resource use efficiency recorded were similar in sole- and double-crops (average 0.85 g m^{-2} mm^{-1} for water and 0.58 g MJ^{-1} for solar radiation). Therefore, water and radiation productivity were associated mainly with resource capture. The inclusion of double-crops led to a more efficient use of the annual offer of resources as reflected by the increased water and radiation productivity in double-crops as compared with sole-crops. Therefore, double cropping appears as a feasible option to increase the whole system efficiency and to improve the return of crop residues as compared with the simplified systems based on soybean of South America.

Keywords: Resource capture efficiency; multiple crops; intensification; water use efficiency; radiation use efficiency.
Abbreviations: DC_double-crops, F_flax, F/S_flax/sequential soybean, LSW_long-season wheat, LSW/S_long-season wheat/sequential soybean, P_pea, PAR_photosynthetically active radiation, P/S_pea/sequential soybean, R_rapeseed, RC_solar radiation capture efficiencies, RP_radiation productivities, RUE_solar radiation use efficiencies, R/S_rapeseed/sequential soybean, SC_sole-crops, SCS_sole-crop soybean, SSW_short-season wheat, SSW/S_short-season wheat/sequential soybean, WC_water capture efficiency, WP_water productivities, WUE: water use efficiency.

Introduction

The cropping systems of the Argentinean Pampas are largely based on soybean as the main crop. The area cropped with soybean has dramatically increased from 32% to 65% in the last 15 years. On the other hand, the area cropped with winter crops has been reduced to as low as 20% (SAGPYA, 2011).
A similar trend is being recorded in other countries of South America, as Uruguay, Bolivia and Brazil (FAOSTAT, 2011). In fact, the soybean/maize ratio of the cropped area is around 2 for Brazil, and 6-7 for Argentina and Uruguay. The predominance of summer crops, particularly soybean, leads to important inefficiencies in the use of the annual available resources for crop production. In fact, in many regions where the length of the growing season and the climatic balance are favorable, an important waste of water and radiation has been documented when a sole crop is sown during the growing season. In sole-crops of the southeastern Pampas of Argentina, the reported capture of annual solar radiation ranges from 24 to 31% whereas that of the water available ranges from 26 to 51 % (Caviglia et al., 2004). Irrespective of the high inefficiency in the resource use of the current cropping systems in South America, the high frequency of soybean in the sequences may seriously affect both the soil carbon storage (Studdert and Echeverria, 2000) and several soil properties (Wright and Hons, 2004; Martens, 2000) involved in the functionality and environmental sustainability of the system. The intensification of agricultural systems in many subtropical and temperate areas of South America by including multiple crops (in sequence or intercrops) may provide a reliable platform to increase resource use efficiency (Caviglia and Andrade, 2010) and improve the sustainability of cropping systems. Sequential crops are defined as those in which a crop is planted in sequence after the harvest of the first component (Andrews and Kassam, 1976). In the Argentinean Pampas, wheat, which is the predominant winter crop, is cultivated in sequential double-crops previous to soybean (SAGPYA, 2011). The use of wheat/soybean double-crops has demonstrated to be an important tool for the improvement of the capture of water and solar radiation

(Caviglia et al., 2004), reaching 53-71% and 38-44% of annual available resource, respectively. However, the double-cropped area in Argentina has remained as low as 20% of the total planted area for the last five years (SAGPYA, 2011). Quantification of the efficiency in the use of resources by crops has been traditionally based on the growing period, i.e. from emergence to physiological maturity (Hunt et al., 1990; Sinclair and Muchow, 1999; Caviglia and Sadras, 2001; Sadras et al., 1991), irrespective of the resource availability out of the growing period. This approach does not take into account the ability of the cropping systems to use the annual available resources. As a consequence, a new, broader approach has been developed to study the impact of several cropping strategies on the whole efficiency in the use of the available resources (Caviglia et al., 2004; Caviglia and Andrade, 2010). This new approach provides a conceptual framework able to integrate the traditional resource use efficiency, i.e. grain yield per unit of captured resource, and the resource capture efficiency, i.e. captured resource per unit of annual available resource. Resource productivity, which represents the amount of grain produced per unit of annual available resource, can be obtained as the product between resource capture efficiency and resource use efficiency. In the southeastern Pampas, the inclusion of sequential wheat/soybean double-crops increases water and solar radiation productivity through an increased resource capture, rather than an increased resource use efficiency (Caviglia et al., 2004), since no differences are expected in crops with a similar photosynthetic metabolism (Sinclair and Muchow, 1999; Caviglia et al., 2011). The inclusion of winter crops other than wheat previous to soybean in sequential double-crops has not been widely researched. This limits the adoption of cropping intensification in the Pampas. Inclusion of reliable alternative winter crops such as peas (*Pisum sativum* L.) rapeseed (*Brassica napus* L.) and flax (*Linum usitatissimum* L.) can be valuable for cropping system intensification to increase the whole efficiency in the resource use and system sustainability. Knowledge of the resource productivity in cropping systems is useful to design efficient and sustainable cropping sequences. There are no studies using the resource productivity as a measure of the whole efficiency of the systems in an annual basis instead of the classical efficiencies based on the crop growing period. This may provide insights in order to propose cropping sequences as alternatives to the increasing simplified cropped area with soybean in South America. The aims of this work were to evaluate water and solar radiation productivity of double-crops with different winter crops and soybean as the second crop and to assess the performance of sole- and double-crops in the use of resource.

Results

Environmental conditions

Heavy rainfall during March (Table 1) could have contributed to the recharge of the soil profile, typical of the region. This allowed adequate water availability during the vegetative growth period of winter crops, despite the low rainfall recorded during June, July and August. During the critical period of winter crops, i.e. September and October, the rainfall recorded was above normal. The incident global radiation was within normal values (Table 1).

Grain yields

The grain yield of sole- or double-crops differed significantly ($P < 0.0001$) (Fig. 1). The highest yields were obtained in double-crops, which outyielded those of sole-crops by 95% in average. Pea both as sole- and as double-crop had the highest yields. Among double-crops, flax/sequential soybean showed the lowest yield as compared with long- or short-season wheat/sequential soybean and rapeseed/sequential soybean (Fig. 1).

Resource productivity and its components

Water and radiation productivity differed significantly between sole- and double-crops ($P < 0.0001$), reaching average values as much as two-fold higher in double crops than in sole-crops (Fig. 2). Average WP was 0.85 g m^{-2} mm^{-1} in double-crops and 0.43 g m^{-2} mm^{-1} in sole-crops (Fig. 2A), whereas RP averaged 0.22 g MJ^{-1} in double-crops and 0.11 g MJ^{-1} in sole-crops (Fig. 2B).

Water and radiation capture efficiencies were greater in double-crops than in sole-crops ($P<0.0001$) (Fig. 3). Among double-crops, WC was higher (3.5%) in flax/sequential soybean than in rapeseed/sequential soybean and pea/sequential soybean. Among sole-crops, WC was 13% higher in flax and short-season wheat than in the remaining sole-crops, including sole soybean (Fig. 3A). Among double-crops, the RC was higher in long season wheat /sequential soybean, pea/sequential soybean and rapeseed/sequential soybean than in the remaining double-crops, whereas among sole-crops, the RC was higher (41%) in sole soybean.

The average recorded resource use efficiencies were higher in sole-crops than in double-crops, although differences were significant only for radiation ($P<0.05$) (Fig. 4). In general, WUE was higher for pea and lower for flax both in sole and double-crops and ranged from 1.15 to 0.64 g m^{-2} mm^{-1}. Radiation use efficiency ranged from 0.42 g MJ^{-1} in sole soybean to 0.68 g MJ^{-1} on average for the other sole-crops, with intermediate values (0.53 g MJ^{-1}) in double-crops.

Relationship between resource productivity and its components

Double-crops had higher WP and RP, which was associated mainly with higher captures ($P < 0.0001$, $r = 0.89$ and $r=0.91$ for water and radiation, respectively). Resource productivities were higher in double- than in sole-crops, considering similar values of resource use efficiency (Fig. 5A and 5B).

Increases in the resource use efficiency (WUE and RUE) had greater impact on the WP and RP in double- than in sole-crops (Fig. 5A and 5B), i.e. there was a higher slope for double-crops, reflecting a more efficient use of the annual offer of resources.

Discussion

In agreement with that previously found in the southeastern Pampas of Argentina (Caviglia, et al., 2004) for the sequential wheat/soybean double-crop, here we found that both WP and RP were higher in double-crops than in sole-crops (Fig. 2A and B). The values of WUE found in this study were similar to those reported in Arkansas, USA (Daniels and Scott, 1991), and in the southeastern Pampas of Argentina (Caviglia, et al., 2004) for the sequential wheat/soybean double-crop, which ranged between 0.8 and

Table 1. Monthly rainfall, mean temperature, and photosynthetically active radiation (PAR) in 2007 as compared to the historical average (1934-2006).

		Months											
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Rainfall	2007	121.5	123.5	524.1	58.8	58	27.1	1.5	18.7	114	119.6	13.7	94
	Historical	117.6	104.6	155.6	105.4	49.8	40.7	29.4	32.3	53.5	106.3	111.5	114.5
mm	Deviation	3.9	18.9	368.5	-46.6	8.2	-13.6	-27.9	-13.6	60.5	13.3	-97.8	-20.5
Temperature	2007	24.6	24.1	21.3	19.1	13.1	11.2	9.5	10.5	17.5	19.7	20	23.5
	Historical	24.8	23.8	21.8	18.1	15.4	12.5	12	13.3	15.2	18	20.8	23.4
ºC	Deviation	-0.2	0.3	-0.5	1	-2.3	-1.3	-2.5	-2.8	2.3	1.7	-0.8	0.1
PAR	2007	10.6	9.7	6.6	5.6	5.2	4.1	5.1	6.1	6.4	8.3	11.6	11.7
	Historical	10.9	9.6	8.4	6.2	5.0	4.2	4.6	5.9	7.6	9.2	10.6	11.4
MJ m^{-2}	Deviation	-0.3	0.1	-1.8	-0.6	0.2	-0.1	0.5	0.2	-1.2	-0.9	1.0	0.3

Data from the meteorological station of INTA Paraná (31.5º S; 60.31º W; 110 m above sea level). Deviation was calculated as the difference between the 2007 value and the historical average for each variable and month.

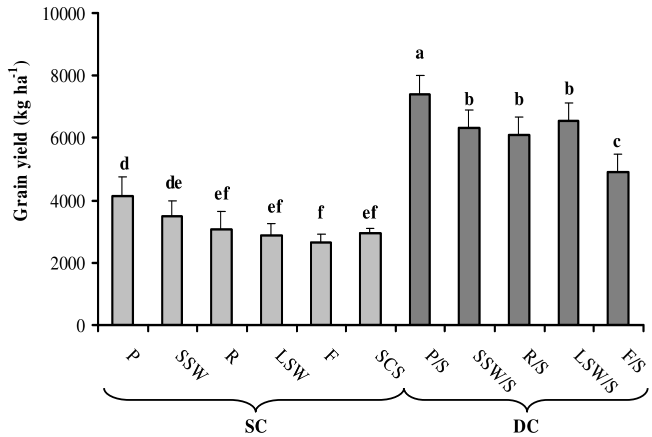
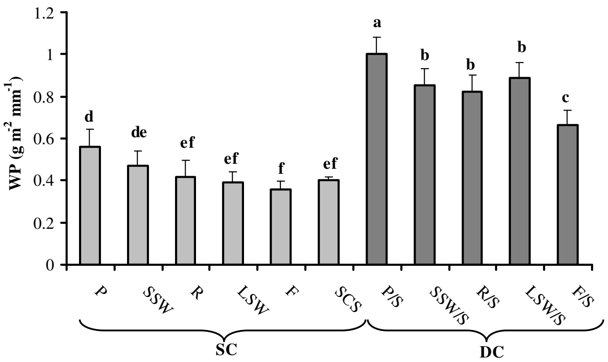
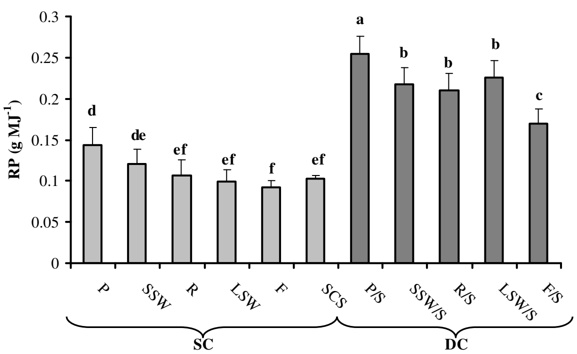


Fig 1. Grain yield of sole- and double-crops. Sole-crops (SC): P: pea, SSW: short-season wheat, R: rapeseed, LSW: long-season wheat, F: flax, SCS: sole-crop soybean; double-crops (DC): P/S: pea/sequential soybean, SSW/S: short-season wheat/sequential soybean, R/S: rapeseed/sequential soybean, LSW/S: long-season wheat/sequential soybean, F/S: flax/sequential soybean. Different letters over the bars indicate differences according to Duncan's test ($\alpha < 0.05$). Error segments over the bars indicate standard deviation.

1.1 g m^{-2} mm^{-1}. The improvements in resource capture had an impact on WP and RP similar to that of resource use efficiency (Fig. 2 and 4). This result shows that the inclusion of crops with greater resource use efficiencies results in an increased productivity in double-cropping systems as compared with systems based on sole-crops, which is in contrast with previous findings, which have indicated a greater impact of capture on resource productivity (Caviglia et al., 2004). However, it has been reported that, in sunflower/soybean and corn/soybean relay-intercrops, WP and RP are also related to resource use efficiency (Coll et al., 2007) and that resource productivity can be improved by the inclusion of more efficient crops, such as sorghum and maize, in the cropping sequence (Caviglia and Andrade, 2010). Therefore, it should be emphasized that the main strategy to improve WP and RP in humid and temperate areas is to enhance the use of the growing season to better exploit the potential environmental productivity. In fact, our results show that the length of the growing period was, on average, 162 days longer in double-crops than in sole-crops. Water capture reached very high values, almost 100% of the annual water offer (Fig. 3A), but radiation capture was only as high as 40% (Fig. 3B). Differences between WC and RC are attributable to the fact that radiation is a non-storable resource, and thus a considerable fraction of the available resource is wasted during the fallow periods. In contrast, water can be stored in the soil during the non-growing periods, allowing crops to take advantage of it later (Caviglia et al., 2004). It should be noted that the results of WC may be repeatable only in conditions of complete recharge of the soil water profile, coupled with a distribution and an amount of rainfall during the year that causes little or no surface runoff or deep drainage. Although many cropping strategies such as manipulation of the seeding rate, row width, and length of the genotype cycle may be used to improve the resource capture during the establishment of a sole-crop, the real impact of those practices is negligible as compared with growing more crops during a season, lengthening the growing period (see Caviglia et al., 2004). This is evident in our results, where the best fit to the annual radiation offer to the sole-soybean cycle allowed the improvement of RC, which, however, was well below the RC of double-crops (Fig. 3B). The winter crops evaluated differed in their WUE and RUE, which is attributable to the energy content in grains and to the canopy architecture. The role of the energetic cost to produce oil and protein in grain in the resource use efficiencies has been discussed elsewhere (see Andrade, 1995; Sinclair and Muchow, 1999; Caviglia et al., 2004). The small differences in resource use efficiencies in both sole- and double-crops (Fig. 4A and 4B) were more related to the energy content of the grains than to the cropping strategy (sole- or double-cropping).



(A)

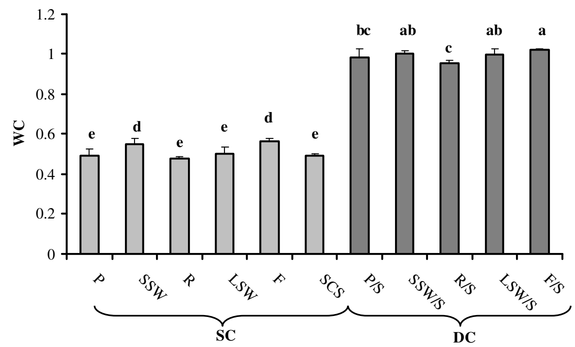


(B)

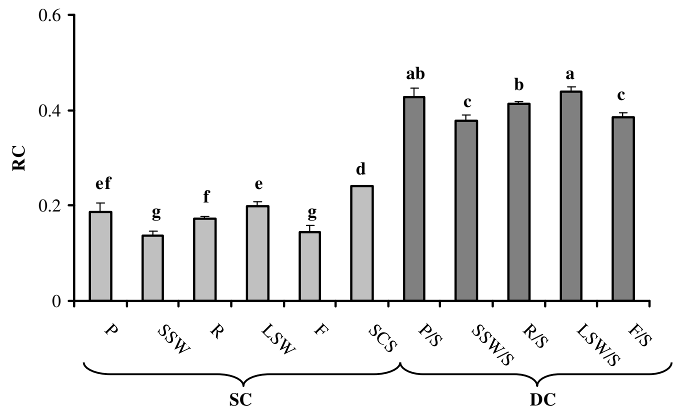
Fig 2. Water productivity (WP) (A) and radiation productivity (RP) (B) of sole- and double-crops. Sole-crops (SC): P: pea, SSW: short-season wheat, R: rapeseed, LSW: long-season wheat, F: flax, SCS: sole-crop soybean; double-crops (DC): P/S: pea/sequential soybean, SSW/S: short-season wheat/sequential soybean, R/S: rapeseed/sequential soybean, LSW/S: long-season wheat /sequential soybean, F/S: flax/sequential soybean. Different letters over the bars indicate differences according to Duncan's test ($\alpha < 0.05$). Error segments over the bars indicate standard deviation.

This reflects that double-crops were as skillful as sole-crops to transform the captured resources in grains. This is not surprising, considering that all the crops, even winter crops as sole soybean, have a C3 photosynthetic metabolism.

At similar values of resource use efficiency, double-crops were more effective than sole-crops to produce grain yield (Fig. 5A and 5B). This advantage of double-crops is conferred by the largest capture (Fig. 2 and 3). This result reinforces the importance of evaluating the whole system efficiencies on an annual basis as compared with the classical approach on seasonal basis, i.e. from crop emergence to physiological maturity. The increase in resource capture has implications not only on the whole system efficiency but also on the environmental outcomes. In fact, it has been suggested that the water that is not used to produce plant material is directly involved in environmental degradation processes such as runoff, leaching of nutrients and pesticides and increased ground water level (Gregory et al., 1992; Nosetto et al., 2011). On the other hand, it is anticipated that the capture of a higher fraction of the annual offer of solar radiation increases the production of plant material, which involves an enhanced carbon input to the soil (Franzluebbers et al., 1998) to improve the soil carbon balance (Studdert and Echeverria, 2000). Due to the growing needs to achieve higher agricultural productivity to meet the increased demands for food in quantity and quality of an increasing global population, the intensification of the systems including more crops per unit of time appears as a fundamental tool, mainly in environments where the resource offer exceeds that required by sole-crops. In this work, we showed strong evidences of the improvements of the whole system efficiencies, which have not only consequences on the system productivity but also important environmental benefits. Our results highlight the importance of using the resource productivity as a measure of efficiency of the systems instead of classical efficiencies on a seasonal basis.



(A)



(B)

Fig 3. Water capture efficiency (WC) (A) and radiation capture efficiency (RC) (B) of sole- and double-crops. Sole-crops (SC): P: pea, SSW: short-season wheat, R: rapeseed, LSW: long-season wheat, F: flax, SCS: sole-crop soybean; double-crops (DC): P/S: pea/sequential soybean, SSW/S: short-season wheat/sequential soybean, R/S: rapeseed/ sequential soybean, LSW/S: long-season wheat/sequential soybean, F/S: flax/sequential soybean. Different letters over the bars indicate differences according to Duncan's test ($\alpha < 0.05$). Error segments over the bars indicate standard deviation.

Materials and methods

Study site

The agroecological features of the Argentinean Pampas are described elsewhere (Caviglia and Andrade, 2010). Briefly, the region located between 28º and 40°S and 68º and 57°W, which is one of the most important areas for agricultural production in the world, is suitable both for agriculture and cattle production (Hall et al., 1992; Viglizzo and Roberto, 1998). The Pampas has a warm temperate climate with adequate to less than adequate rainfall. Mean annual rainfall increases from SW to NE, ranging from 400 mm in the SW to more than 1200 mm in the NE, whereas the rainfall regime shifts from monsoonal in the NW to more evenly distributed in the SE (Hall et al., 1992). Mean annual temperatures increase from about 13.5ºC in the south to 18.5°C in the north of the region (Hall et al., 1992). The soils of the Argentinean Pampas belong predominantly to the order of Mollisols, being Argiudols and Haplustols the most representative ones. Most soils are developed from loessic sediments, and show a gradient in texture from sandy and sandy-loam in the southwest to clay and clay-loam in the northeast (INTA-SAGyP, 1990). The experiment was carried out at INTA Research Station, Paraná, Argentina (31.5º S; 60.31º W; 110 m.a.s.l) during the 2007/08 cropping season. The soil was a fine, mixed, thermic Aquic Argiudoll under no till since 1998. The soil organic matter content was 3.2% and the pH was 6.8. (0-0.20 m depth). Corn was the crop preceding the experiment.

Treatments and experimental design

Treatments included five winter crops: short- and long-season spring bread wheat (*Triticum aestivum* L.), flax (*Linum usitatissimum* L.), pea (*Pisum sativum* L.) and rapeseed (*Brassica napus* L.). The crops were sown on 16 May 2007, except for short-season wheat, which was sown on 12 July 2007. After harvest of these crops, soybean (*Glycine max* L.) was planted on 30 November 2007, both as a sequential double-crop and as a sole-crop, since early harvest of winter crops in our region is coincident with the optimum planting date for soybean as a sole-crop. A control without crops during winter was also included in order to evaluate the effect of soybean as a sole-crop. We used a complete block design with four replicates. The experimental unit size was 13.2 m^2.
Cultivars used were BIOINTA 3004 (long season) and BIOINTA 1002 (short season) for wheat, Panambí for flax, Impact for rapeseed and an unidentified cultivar for pea. The seeding rates were 280 and 360 seeds m^{-2} for wheat (long and short season, respectively), 1000 seeds m^{-2} for flax, 200 seeds m^{-2} for rapeseed, 120 seeds m^{-2} for pea and 32 seeds m^{-2} for soybean. Row spacing was 0.22 m for winter crops and 0.53 m for soybean. Before the beginning of the experiment, the levels of N-NO_3^- and extractable phosphorus (Bray-Kurtz Nº1) were assessed in soil samples taken at 0.60 m depth, every 0.20 m. Average soil N-NO_3^- available at sowing was 31.2 kg N ha^{-1}, whereas extractable P levels were above the critical level for all winter crops, even for wheat, which has the highest P requirements. As a consequence, no P fertilizer was applied. The winter crops studied, including pea, were fertilized with broadcasted urea as N source after planting, at rate of 100 kg N ha^{-1}. The experiment was kept free of insects, diseases and weeds, using locally recommended control practices when needed.

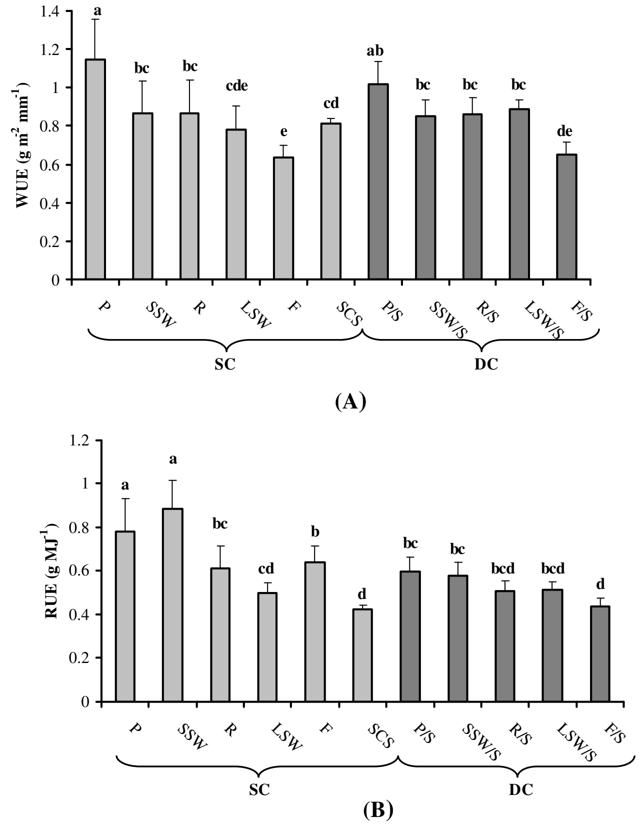
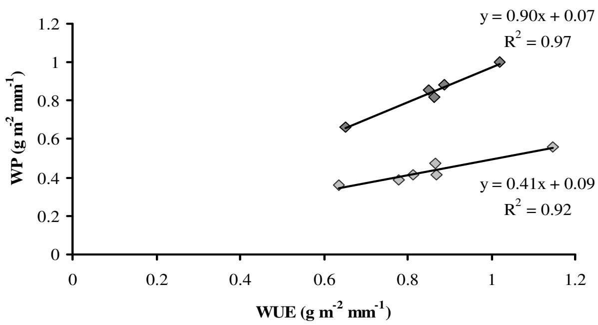


Fig 4. Water use efficiency (WUE) (A) and radiation use efficiency (RUE) (B) of sole- and double-crops. Sole-crops (SC): P: pea, SSW: short-season wheat, R: rapeseed, LSW: long-season wheat, F: flax, SCS: sole-crop soybean; double-crops (DC): P/S: pea/sequential soybean, SSW/S: short-season wheat/sequential soybean, R/S: rapeseed/sequential soybean, LSW/S: long-season wheat/sequential soybean, F/S: flax/sequential soybean. Different letters over the bars indicate differences according to Duncan's test ($\alpha < 0.05$). Error segments over the bars indicate standard deviation.

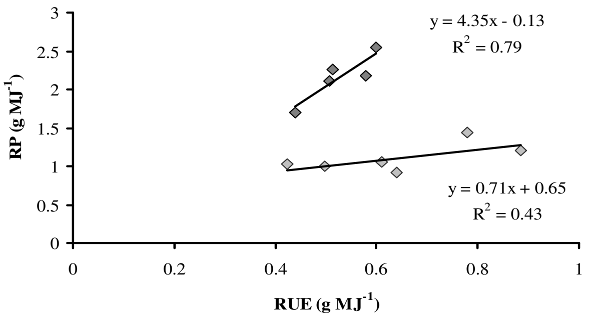
Measurements and calculations

The phenological development of crops was weekly recorded to determine the key stages in crop development (Zadoks et al., 1974 for wheat; Freer, 1991 for flax; Weber and Bleiholder, 1990 for rapeseed and Knott, 1987 for pea).
At physiological maturity, samples were taken to determine grain yield, its numerical components, i.e. grain number per unit area and individual grain weight, and total shoot biomass. The harvest index (HI) was calculated as the ratio between grain yield and total shoot biomass.
Photosynthetically active radiation (PAR) interception by crops was determined every two weeks, using a linear quantum sensor (Cavadevices, Buenos Aires, Argentina), taking readings on (Io) and beneath the canopy, at the level of the last green leaves (It). The percentage of daily radiation intercepted was calculated as:

$$\text{Intercepted PAR (\%)} = \frac{(\text{Io average It})}{\text{Io}} \times 100 \qquad [1]$$



(A)



(B)

Fig 5 . Water productivity (WP) as a function of water use efficiency (WUE) (A) and radiation productivity (RP) as a function of radiation use efficiency (RUE) (B). Light-gray diamonds (◇) indicate sole crops and dark-gray diamonds (◆) indicate double crops.

Intercepted photosynthetically active radiation (IPAR) during the crop cycle was estimated as:

$$\text{IPAR} = \sum_{PM}^{E} IPARi \qquad [2]$$

where E and PM represent crop emergence and physiological maturity, respectively and IPARi indicates the daily intercepted PAR. Daily intercepted PAR, in turn, was estimated as the product of daily incident PAR (global radiation * 0.48) and the daily interception percentage, estimated by fitting polynomial functions between intercepted photosynthetically active radiation (Eq [1]) and days from emergence of each crop. Soil samples were taken at 1.2 m depth, at intervals of 0.1 m, every two weeks, to determine the soil water content, using the gravimetric method in all plots. Evapotranspiration (ET) was estimated through a water balance considering the variation of soil water storage between two measurements and effective rainfall without considering deep percolation. The effective rainfall was estimated based on data from runoff plots close to the experiment (< 500 m), i.e. using a correction factor derived from actual rainfall and runoff measured in winter crops (Caviglia and Sadras, 2011). Water and solar radiation use efficiencies (WUE and RUE, respectively) were estimated as the ratio between grain yield and the amount of resource captured during the growing season (ET or IPAR) in sole- (winter crops or sole soybean) and double-crops (winter crop/sequential soybean). Water and solar radiation capture efficiencies (WC and RC, respectively) were estimated as the ratio between the amount of resource captured (ET or IPAR) and the annual resource offer i.e. annual rainfall or annual incident PAR, considering the period from 1 May 2007 to 30 April 2008 (Caviglia et al., 2004). Water and radiation productivities (WP and RP, respectively) were estimated as the product between resource use efficiency (WUE or RUE) and capture efficiency (WC or RC).

Statistical analysis

Data were analyzed using analysis of variance, mean comparison tests (Duncan α= 0.05), correlation analysis and linear regression, using procedures included in the SAS statistical package (SAS, 2000).

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